Techniques for Soldering to Aluminum

Aluminum solder connections are discussed

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Aluminum oxidizes with extreme rapidity; it is almost impossible to remove its ever-present oxide coating more rapidly than it reforms. This oxide, aluminum oxide Al_2O_3, is extremely tenacious; it melts at 2050°C (3722°F). Aluminum oxide is neither melted nor reduced by temperatures that melt the metal. However, oxides normal to mill-finished aluminum alloys are removed during soldering by specialty aluminum cleaners and soldering fluxes (Ref. 1).

There are many elements used to combine with aluminum to make different alloys, and they are used to enhance given properties of the aluminum. Silicon is added to lower the melting point and, more importantly, improve the extrusion properties of aluminum alloys. Magnesium is added to improve the strength of the aluminum alloy; the same is true for zinc and titanium. The problem is that the addition of most of these elements decreases the interaction with pure aluminum and, in the case of silicon, magnesium, and titanium, can significantly reduce the solderability of those particular alloys because of the inherent poor solderability of these elements (Ref. 2).

The major consideration when selecting a soldering filler metal is if it will make a metallurgical bond with the aluminum. If this does not occur, the bond to the aluminum will fail. The common soldering filler metals that have been found to properly bond to aluminum contain zinc, silver, and copper. Cadmium will bond to aluminum, but its highly toxic nature precludes its use. Neither tin nor lead will alloy to aluminum as a solder, so a simple tin-lead soldering filler metal should be avoided when soldering directly to aluminum. Typical soldering filler metals that work well for alu-

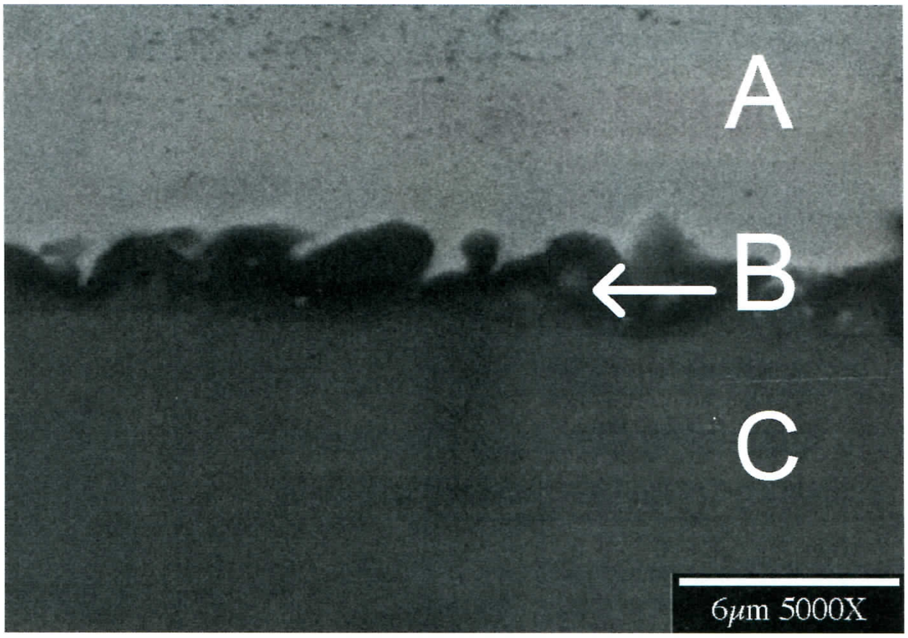

Fig. 1 — An unplated aluminum surface soldered with 91/9 tin-zinc. A — 91/9 tin-zinc soldering filler metal; B — zinc/aluminum intermetalic zone; C — aluminum base metal.

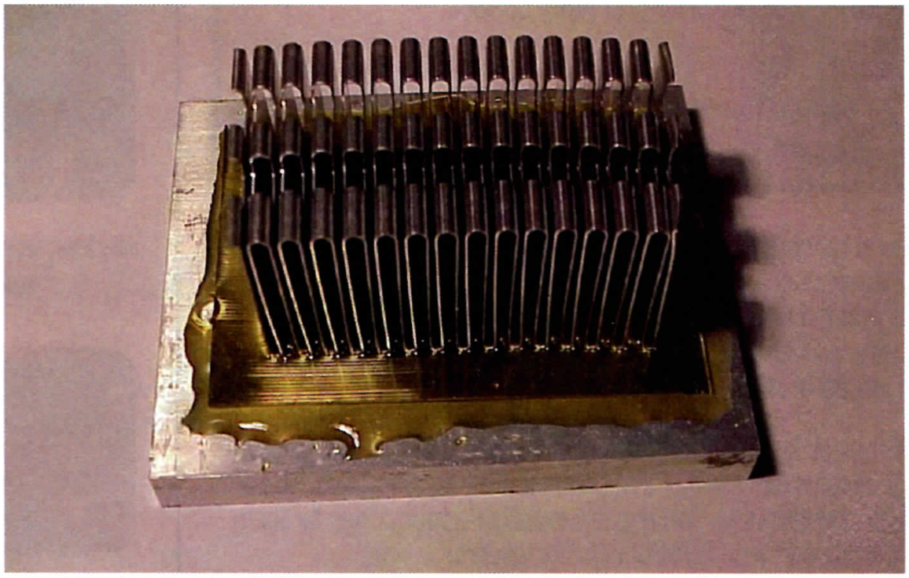

Fig. 2 — Liquid flux applied to the surface between two aluminum parts with a solder foil present.

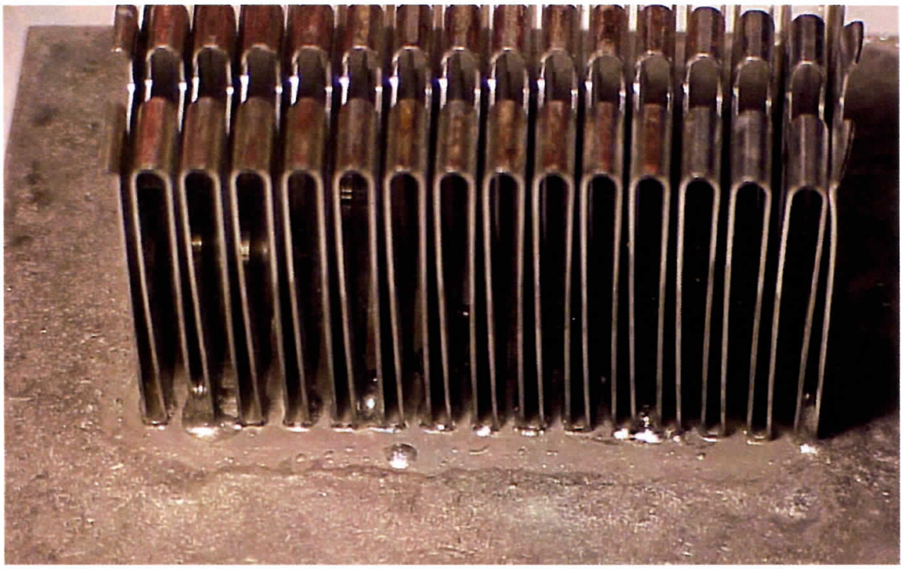

Fig. 3 — After hot plate heating, the soldering filler metal has flowed and connected the aluminum parts.

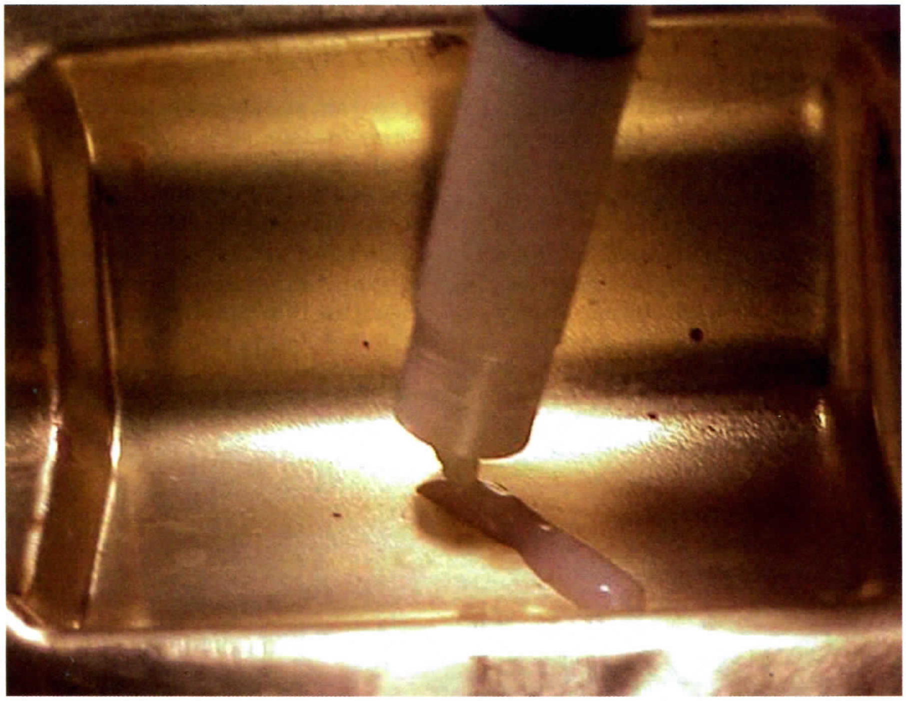

Fig. 4 — Paste flux dispensed to a metal surface.

minum soldering include tin-silver, tin-copper-silver, tin-copper, and tin-bismuth-silver. A low-cost alloy and simple plumbing alloy like tin-antimony will not work because neither tin nor antimony will bond metallurgically to aluminum. Any soldering filler metal will work if one first pre-tins the surface with a proper solder, then solders over the pre-tinned surface. Properly soldering to aluminum means making an intermetallic bond between the solder alloy used and the aluminum surface.

In Fig. 1, a 91/9 tin-zinc soldering filler metal is used to solder to aluminum. The solder joint was cross sectioned, polished, then placed in a scanning electron microscope to show the intermetallic bond between the solder alloy and the aluminum surface. The intermetallic connection is actually a new compound that is neither soldering filler metal nor aluminum (Ref. 3).

Results and Discussion

Methods for Soldering to Aluminum

Liquid flux and solder — The liquid flux for aluminum soldering is a mixture of organic amines and inorganic fluoroborate salts that typically has the consistency of honey and whose color may range from amber to deep brown. Other chemicals, such as alcohols, are sometimes added to modify the viscosity of the flux for those operations that require a less viscous flux — Figs. 2 and 3. Organic flux formulations are designed for temperatures of 177° to 316°C (350° to 600°F). Above this temperature, the flux begins to carbonize at an ever increasing rate. At 316°C (600°F), deterioration and charring are so rapid that organic flux can only be used with ultra-rapid soldering techniques, such as induction soldering (Ref. 5).

Paste flux and solder — When chemical binders are added to the liquid flux, it transforms the state of the flux, making it a paste — Fig. 4. The paste is readily dispensable by a needle, which allows for more accurate placement of the flux (Ref. 6).

Flux-cored soldering filler metal — When the organic flux formulation is further modified to have a higher solids content, it will be more viscous, instead of being liquid at room temperature. When this material is heated, it will liquefy, which allows it to be injected into a solder core. Once the filler metal wire is cooled, the flux core becomes hard, allowing the wire to be used as a flux-cored soldering filler metal. The chemistry of this modified flux solid is activated for soldering aluminum at the 280° to 380°C (536° to 716°F) temperature range. The flux-cored aluminum soldering filler metal is different than typical flux-cored soldering filler metal for copper in that the aluminum itself must be heated to the activation temperature before melting the core filler metal solder on the hot surface — Figs. 5 and 6. The chemistry of the flux will not allow it to be melted onto a soldering iron, as is often done with flux-cored soldering of copper surfaces (Ref. 7.)

Soldering filler metal paste — One advantage of an organic type of flux is that it can be converted to a soldering filler metal paste by incorporating solder powder and binders — Figs. 7 and 8. The same temperature limitations, 180° to 316°C (350° to 600°F), apply to most versions of this solder filler metal paste. A high-temperature soldering filler metal paste has been developed and formulated to have activating temperatures in the 280° to 380°C (536° to 716°F) range, and can withstand up to 420°C (788°F) (Ref. 8).

Heating Methods for Soldering Aluminum

Hot plate — A hot plate may be used to bring aluminum parts up to soldering temperature. Such a device can vary from being thermostatically controlled electric devices, noncontrolled electric units, and even metal plates set over gas jets. Parts to be soldered are cleaned, fluxed, and positioned. The soldering filler metal may be preplaced or face-fed. In the latter event, the parts themselves must have sufficient weight to remain immobile while the soldering filler metal contacts them, or they must be kept in position by suitable fixtures. Heat is applied, and when the soldering filler metal melts and flows through the joints, the heat is turned off. If the heat is not automatically controlled, but is manually shut off, it is generally done a little before the joint is complete to prevent overheating (Ref. 9).

Convection oven — Furnace soldering lends itself to both small-lot and high-volume production. As many assemblies and joints as can fit into the furnace may be soldered at one time. If the batch furnace's pass-through rate is too low, a semiautomatic continuous furnace is substituted. Parts too large or massive to be evenly heated by other means may be soldered with minimum distortion in a furnace. A furnace is also useful for soldering complex and intricate parts with joints that cannot be easily heated after assembly by other techniques. Solder reflow via conveyor belt oven is a proven and widely used procedure for consistent and reliable soldering. Furnace soldering is excellent for long solder joints, producing highly controlled solder fillets, neater joints, and more efficient use of solder. Any furnace capable of encompassing the assembly to be soldered, bringing it up to the melting temperature of the soldering filler metal used and holding it there for the necessary time may be used. It may be heated by any means including infrared lamps, convection heated air, and static heating coils. Soldering furnaces should be power ventilated. Flux vehicle vapors, such as are given off by alcohol and other organics, are highly combustible and explosive when mixed with air. These vapors can sometimes be eliminated by drying the flux assembly in air prior to soldering. Flux fumes, produced dur-

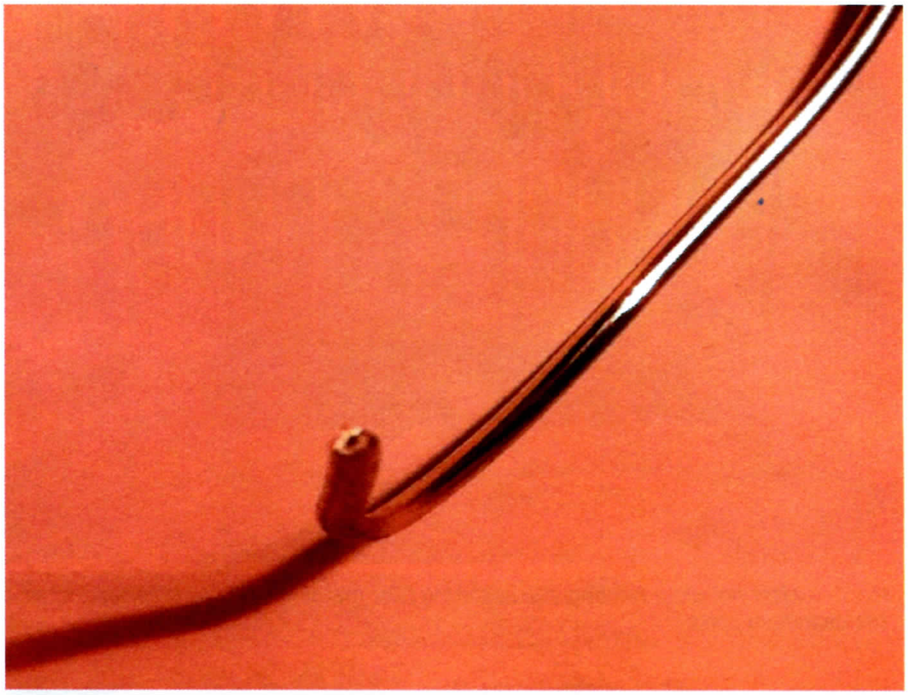

Fig. 5 — Soldering filler metal with aluminum cored flux in the center.

Fig. 6 — Soldering aluminum to aluminum with a soldering filler metal containing cored flux.

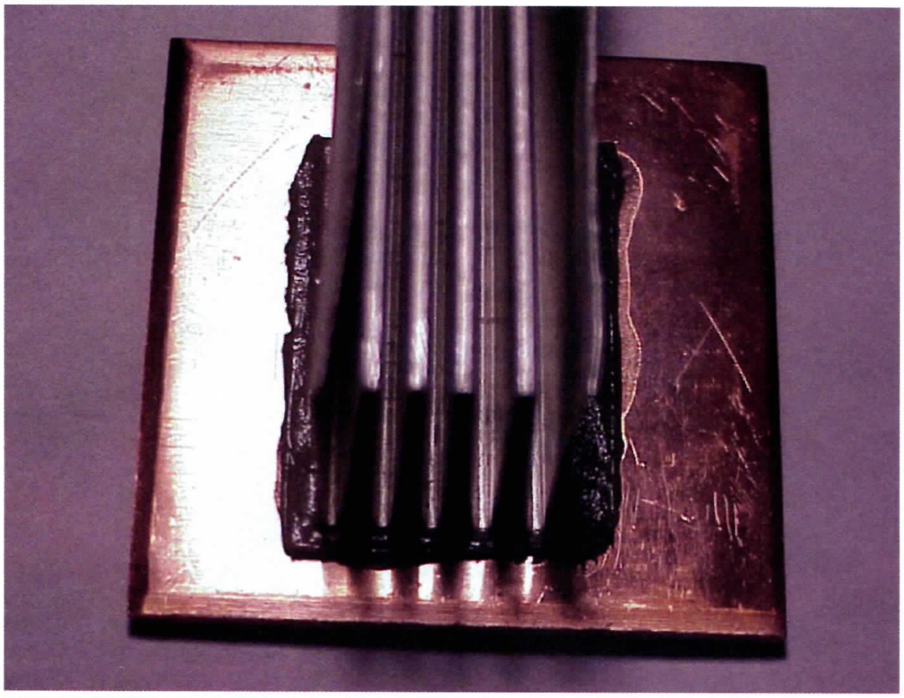

Fig. 7 — An aluminum fin placed on a soldering filler metal paste dispensed on copper.

ing soldering, cannot be as easily avoided. They must be vented outside the plant with attention to local antipollution laws, and may require the installation of scrubbers (Ref. 10).

Induction — Joints soldered by this method are brought to soldering temperature by high-frequency electrical currents induced in the faying surfaces by an inductance (coil) positioned nearby. Heating is localized, fast, and generally accomplished in a few seconds. There are no open flames, and power is consumed only during the soldering cycle. Once soldering parameters have been ascertained, soldering by induction is an extremely accurate and repeatable operation, which can be automated. Post-induction soldering cleaning is easier than post-torch soldering cleaning because there are less combustion products to react with the flux and form insoluble residues. However, the equipment required is expensive compared to other soldering methods (Ref. 11).

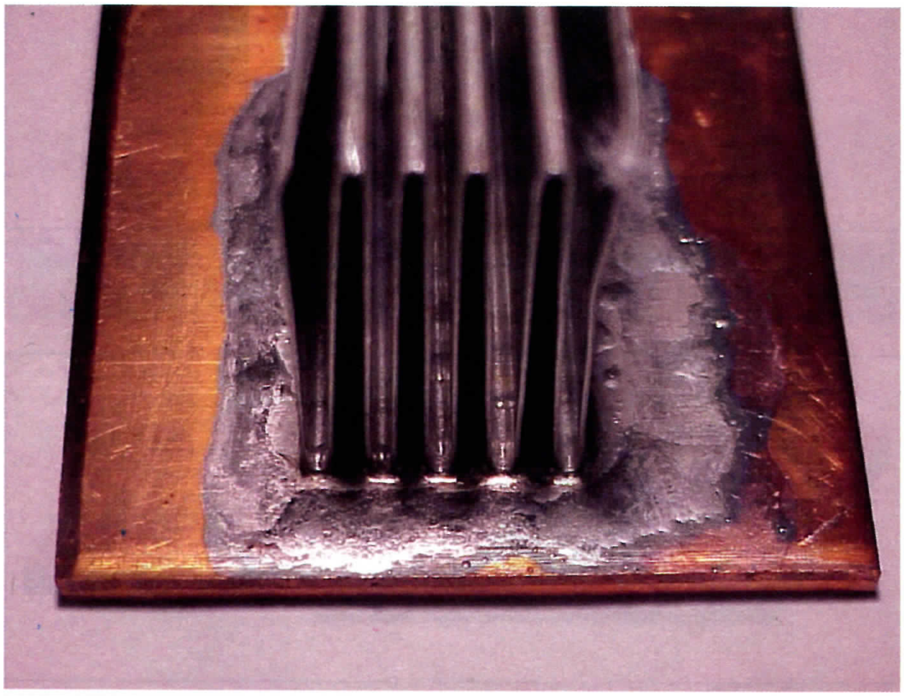

Fig. 8 — After solder reflow, fins are soldered to copper.

Resistance — With resistance soldering, an intense heat can be rapidly developed directly within the joint area and in a tightly controlled manner because the heat is created by passing a current through the metal being heated. This allows a faster ramp-up to the required soldering filler metal melt temperature and minimizes thermal travel away from the solder joint. This helps minimize the potential for thermal damage to materials or components in the surrounding area. Heat is only produced while each joint is being made, making resistance soldering more energy efficient. Resistance soldering equipment, unlike conduction irons, can be used for difficult soldering applications where significantly higher temperatures may be required. This makes resistance soldering comparable to flame soldering in some situations. When the required temperature can be achieved by flame or resistance methods, the resistance heat is more localized because of direct contact, whereas the flame will spread the heat, thus warming a larger area.

Torch — This is the simplest way to provide soldering heat. It is low in cost, portable, and suited to production work as well as single assemblies and repairs. Its flame is hot enough to be used readily with all soldering filler metals, and its output can be varied to accommodate small and large assemblies. Although any source of heat can be used for torch soldering, commercial torch soldering is generally accomplished with the same type of torch, controls, and gases that are used for fusion welding. Conversion to aluminum merely requires a change in torch nozzles. Since the chemicals used to make the relatively low-temperature fluxes, soldering filler metal paste, and cored-wire soldering filler metals are partially organic, they will ignite if exposed to an open flame. For this reason, torch heat should only be used to heat the surface before applying the soldering media. After this, any torch heat applied must be directed away from the joining area, either behind the metal or far away from the metal, to prevent igniting the flux component (Ref. 12).

Soldering iron — A soldering iron may be used; it may be heated electrically or by a gas flame. However, the weight of the copper and its temperature is most important. It must be both large and hot enough to bring the joint and much of the adjoining metal up to soldering temperature in a fairly short time. The use of an iron is therefore limited by the size of practical existing irons and the mass of the workpieces to be soldered. Generally, soldering irons are used only with soft and intermediate soldering filler metals and only on relatively low mass materials. To secure maximum heat transfer and to prevent undesirable alloying, the tip of the iron should be tinned with the soldering filler metal that is to be used (Ref. 13).

Cleaning Aluminum

Aggressive cleaners — These can be either caustic (basic) or strong acid solutions. A hazardous and corrosive caustic deoxidizer may be made by mixing a 5% solution of sodium hydroxide and water, generally kept at 67°C (150°F). The strong acid cleaning systems (of nitric acid or a combination of nitric acid and hydrofluoric acid) are always followed by multiple water rinses to stop the activity of the strong acid cleaner on the aluminum. The problem with such cleaning solutions is that they are dangerous to handle and the raw chemicals to make them are extremely hazardous. After cleaning, water is used to wash the chemicals involved away from the cleaned aluminum.

Hot water — This method is used with the chemistry of the organic "honey" flux. If the parts are immediately washed in hot water, the flux can generally be removed. However, the use of hot water will not effectively remove this type of flux residue if the residues are not immediately removed after soldering.

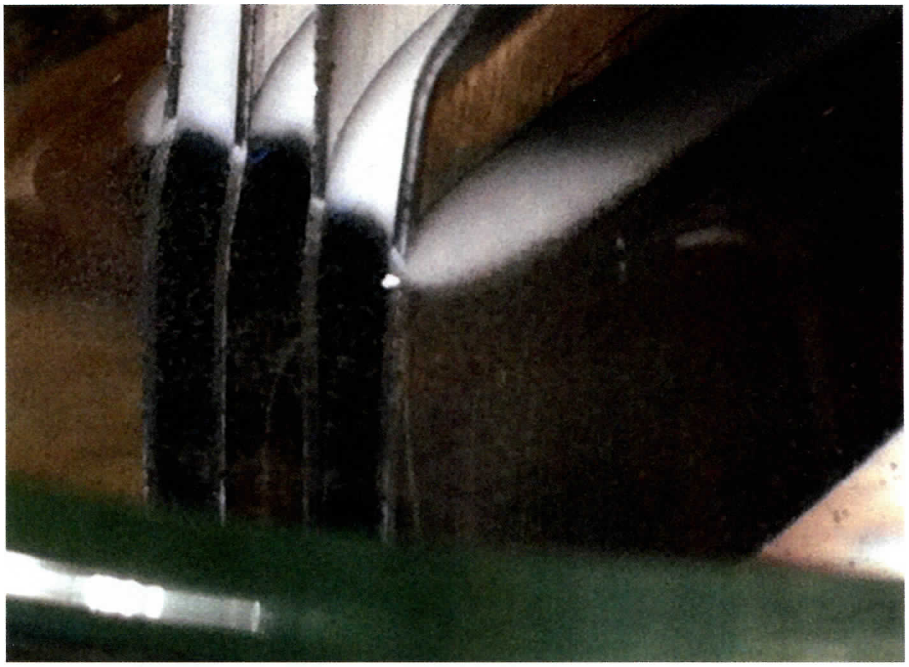

Fig. 9 — Nonhazardous cleaner removing oxides from aluminum. The formation of small bubbles shows the reaction occurring.

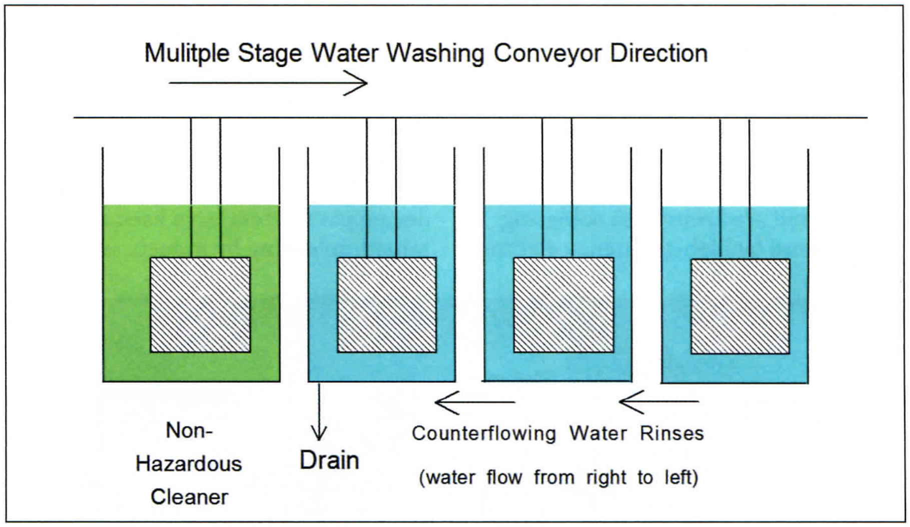

Fig. 10 — Cleaning schematic for multiple-stage nonhazardous cleaner with counterflowing water rinses to make the last tank of water as clean as possible.

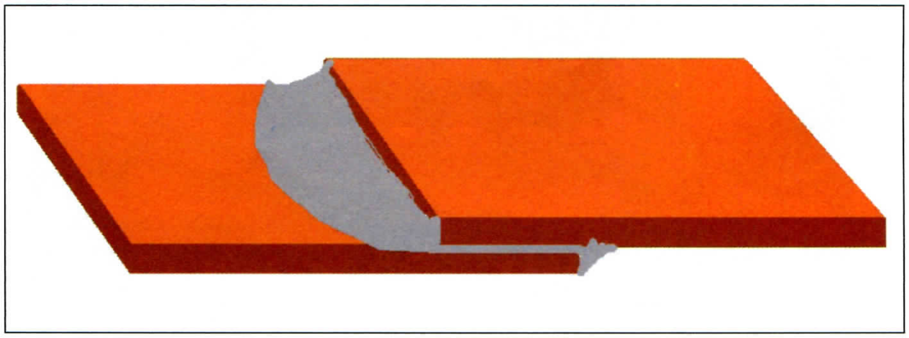

Fig. 11 — Copper to copper lap joint.

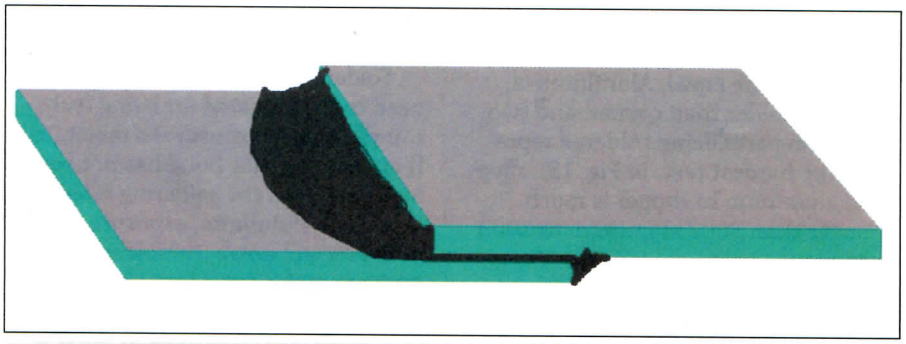

Fig. 12 — Aluminum to aluminum lap joint.

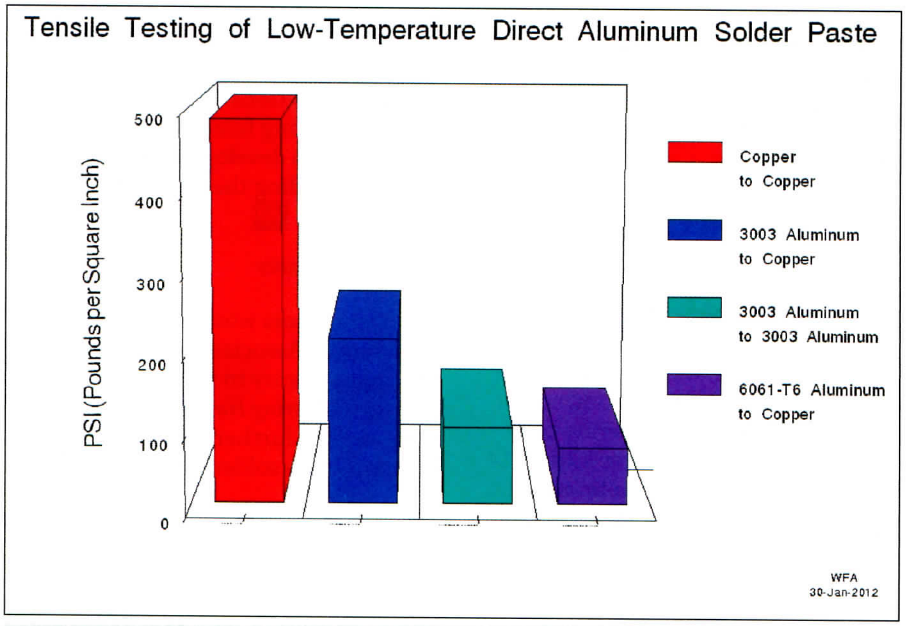

Fig. 13 — Tensile testing of low-temperature direct aluminum soldering filler metal paste.

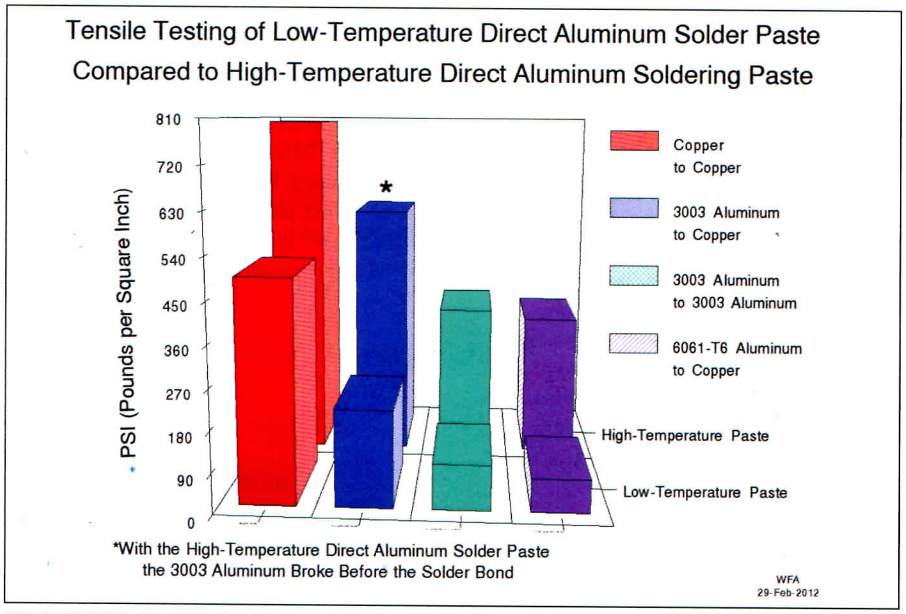

Fig. 14 — Tensile testing of low-temperature direct aluminum soldering filler metal paste compared to high-temperature direct aluminum soldering filler metal paste.

Nonhazardous cleaners — A new chemical cleaner has been developed, using citric acid chemistry, that is not like the strongly corrosive and hazardous cleaners previously used, and works well on the organic "honey" type of soldering chemistry — Figs. 9 and 10. This cleaner is nonhazardous and can be handled with much greater ease than the dangerous caustic or acidic cleaners (Ref. 14). This cleaner is also safer to the environment.

Environmental Exposure

Exposure to moisture — A major consideration in making any aluminum soldered connection is, "how viable is the solder connection?" Experience has shown that just making a connection where the solder has appeared to flow on the aluminum is not sufficient to prove the connection is truly sound. Sometimes after creating the connection, the soldering filler metal can de-bond over a short period of time. When this occurs, the proper amount of attention has often not been given to the conditions needed to make a viable solder joint. If the wrong soldering filler metal is used (no element to create the intermetallic bond to the aluminum), there will be no true soldered connection between the bulk soldering filler metal and the aluminum. Such a connection cannot last because true soldering has not occurred. If insufficient heat is used to create the joint, a cold joint will occur and aluminum is far less forgiving to having the proper conditions for soldering than copper.

To prove if a soldered connection has worked, a week-long exposure to a high-humidity environment (80–95% humidity at 40°C (104°F)) will separate sound solder connections from false ones. Only a connection with a true intermetallic bond will survive the week-long humidity test.

Exposure to salt — Another major consideration for applications, particularly automotive and marine applications, is the ability for a soldered aluminum connection to withstand exposure to a salt environment. This is not an issue for brazed connections (made with a low-melting aluminum alloy containing, for example, 12% silicon) or a so-called "hard solder" containing a unique high-melting solder alloy made of zinc and aluminum. However, when it comes to conventional soldering filler metals used to solder aluminum that may be tin-zinc, tin-silver, tin-copper, tin-silver-copper, or tin-silver-bismuth, testing has shown that all of these soldering filler metals, as well as everything else of standard soldering filler metal types tested, failed to withstand long exposure to 2–10% salt solutions, after a one to three week immersion at room temperature. Some of the proposed exotic protection schemes to prevent salt exposure, such as coating the part after soldering or pretinning the aluminum before soldering, were not practical and did not protect the aluminum soldered connection.

A new solder alloy, ALUSAC-35 (Ref. 15), based on tin-silver-copper, but having other proprietary elements added, has proven it can withstand the difficult room-temperature immersion test. Indeed, this new solder alloy also withstands the ASTM B117 salt fog test (Ref. 16) (the automotive industry elevated temperature salt environment test). This test is in an enclosed chamber with a solution of 2–10% salt water that is heated to 40°C (104°F) and is constantly sprayed on the soldered parts in the chamber for a given time period (usually 24, 48, or 96 h). The requirement is that the solder joint does not break apart under these conditions. The new solder alloy has a relatively high melting temperature of 341°C (646°F).

Strength of Solder Joint

Aluminum to copper — The copper to copper solder bond is stronger than any of the combinations that follow. That is not surprising considering how easy copper is to solder and copper's easy ability to make an intermetallic bond to the solder. The testing used two flat sheets soldered to make a lap joint — Figs. 11 and 12. However, when considering copper to aluminum, these also can be a relatively consistent bond, but it tends not to be as strong as copper to copper, because on strips of the same size, copper is stronger than aluminum. When the tensile test is done, many times the break in the connection is actually in the body of the aluminum, not in the solder bond.

Aluminum to aluminum — This is always the weakest connection if all factors are equal. Aluminum is harder to solder than copper, and two aluminum parts being soldered represents the hardest test. In Fig. 13, alloy 3003 aluminum to copper is much stronger than 3003 aluminum to 3003 aluminum.

Effect of aluminum alloy on final joint strength — The aluminum alloy chosen is an extremely important factor in how strong a given soldered connection will be. As can be seen in Figs. 13 and 14, 3003 aluminum to copper bond is much stronger than the 6061 aluminum to copper bond. The 6061 aluminum to copper bond is slightly weaker than the 3003 aluminum to 3003 aluminum bond, which is surprising.

Effect of soldering method on final joint strength — By soldering technique, there is the consideration of what chemistry and solder alloy is used, and the soldering temperature employed. Figures 13 and 14 show a comparison of low-temperature direct aluminum soldering filler metal paste (using a low-temperature solder alloy), to a relatively high-temperature direct aluminum soldering filler metal paste, using a different flux chemistry and solder alloy. These differences have a great effect on the strength of the solder bond achieved (Ref. 17).

Conclusions

Direct aluminum soldering eliminates the need to plate the aluminum before soldering. When soldering aluminum, it is important to consider the challenges of the tenacious aluminum oxide layer, the differences in aluminum alloys, and choosing the right solder alloy to properly bond to aluminum. There are different techniques now available to solder aluminum, including liquid flux and soldering filler metal, paste flux and soldering filler metal, soldering filler metal paste, and cored-wire soldering filler metal. Similarly, there are many heating methods that will work on soldering aluminum. Once the soldering is completed, there are relatively simple and nonhazardous cleaning methods for removing flux residues.

Soldered aluminum connections need to be evaluated for being truly complete after exposure to moisture. If an intermetallic bond has not been made between the soldering filler metal and the aluminum, exposure to moisture will break the solder bond. Another major consideration is the relative strength of the soldered connection, especially compared to the copper-to-copper bond. The copper-to-aluminum bond is stronger than an aluminum-to-aluminum bond. The aluminum alloy used is a controlling factor in the ultimate strength of these connections. Finally, a new specialty soldering filler metal, ALUSAC-35, has been developed that is capable of withstanding the ASTM B117-16 salt fog test. WJ

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